ARE GIANT PLANETS FORMING AROUND HR 4796A?

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ABSTRACT

We have obtained *FUSE* and *HST* STIS spectra of HR 4796A, a nearby 8 Myr old main sequence star that possesses a dusty circumstellar disk whose inclination has been constrained from high resolution near-infrared observations to be $\sim17°$ from edge-on. We searched for circumstellar absorption in the ground states of C II $\lambda1036.3$, O I $\lambda1039.2$, Zn II $\lambda2026.1$, Lyman series H_2, and CO (A-X) and failed to detect any of these species. We place upper limits on the column densities and infer upper limits on the gas masses assuming that the gas is in hydrostatic equilibrium, is well-mixed, and has a temperature, $T_{gas} \sim 65$ K. Our measurements suggest that this system possesses very little molecular gas. Therefore, we infer an upper limit for the gas:dust ratio (≤4.0) assuming that the gas is atomic. We measure less gas in this system than is required to form the envelope of Jupiter.

Subject headings: stars: individual (HR 4796A)— circumstellar matter— planetary systems: formation

1. INTRODUCTION

Planets, asteroids, and comets are believed to form in circumstellar disks around stars with ages <few 100 Myr. Current (uncertain) models suggest that Jovian planets form either via rapid gravitational collapse through disk instability within a few hundred years (Boss 2000) or via coagulation of dust into solid cores within the first ~1 Myr and accretion of gas into thick hydrogen atmospheres within the first ~10 Myr (Ruden 1999). At present, the timescales on which giant planets form and accrete their atmospheres have not been well constrained observationally. Studies of objects with ages ~10 Myr afford the opportunity to constrain the timescale for gas dissipation around young stars and therefore the timescale for giant planet formation.

Although the circumstellar disks around pre-main sequence stars possess both gas and dust, the circumstellar disks around main sequence stars may be gas poor. Millimeter searches for CO around stars with ages 1 - 10 Myr suggest that within a few Myr, less than a Jupiter mass of molecular gas remains in the circumstellar environment (Zuckerman, Forveille, & Kastner 1995). However, CO may be depleted in the outer regions of disks because it freezes out onto dust grains at temperatures, $T_{gas} \sim 20$ K. Since gas with interstellar or solar abundance is mainly composed of hydrogen and H_2 does not freeze onto grains, recent searches for circumstellar gas have focused on H_2. *ISO* searches for emission from the S(0) and S(1) transitions of H_2 at 28 μm and 17 μm respectively, suggest that 50 - 2000 $M_\oplus$ H_2 exists around β Pic, 49 Cet, and HD 135344 (Thi et al. 2001). However, *FUSE* searches for H_2 absorption in the Lyman band toward β Pic place upper limits on the column density of H_2, N(H_2) $\leq10^{18}$ cm^{-2}, which is 3 orders or magnitude lower than that inferred from *ISO* (Lecavelier des Etangs et al. 2001). The Thi et al. (2001) results not only apparently conflict with the ultraviolet H_2 measurements but also with millimeter emission line studies which suggest that β Pic possesses

$<10^{-5}$ $M_\oplus$ CO (Liseau & Artymowicz 1998). Ground-based follow-up of *ISO* H_2 detections toward Herbig Ae and T-Tauri stars yielded upper limits which were smaller than *ISO* detections (Richter et al. 2002), suggesting that the H_2 must lie in an extended cloud. However, an H_2 cloud around β Pic should have produced a detectable ultraviolet absorption line (Jura 2003). Recently, fluorescent H_2 Lyman-band emission has been detected from the surface layers of the circumstellar disk around the ~10 Myr old star TW Hydrae (Herczeg et al. 2002) using *HST* STIS. We have carried out a *FUSE* and STIS search for circumstellar molecular and atomic gases around the ~8 Myr (Stauffer et al. 1995) debris disk object HR 4796A, another member of the TW Hydrae Association, to help constrain the gas dissipation timescale.

HR 4796A is a main sequence A0V star with a *Hipparcos* distance of 67.1 pc (see Table 1 for a summary of stellar properties) and a fractional dust luminosity L_{IR}/L_* = 5×10^{-3} (Jura et al. 1998). Submillimeter observations suggest that it possesses ≥0.25 $M_\oplus$ dust (Greaves et al. 2000), more circumstellar dust than any other main sequence A-type star in the Yale Bright Star Catalog (Jura et al. 1991). High resolution scattered light imaging has resolved a narrow, dusty ring at 70 AU from HR 4796A with an inclination of $\sim17°$ from edge-on (Schneider et al. 1999). High resolution mid-infrared imaging has resolved the disk in thermal emission (Koerner et al. 1998; Jayawardhana et al. 1998). The presence of a central clearing (Jura et al. 1998) and of a brightness asymmetry from the two lobes of the disk (Telesco et al. 2000; Weinberger, Becklin, & Schneider 2000) have led to speculation that the circumstellar disk possesses a planetary companion at ≤70 AU (Wyatt et al. 1999). Blackbody fitting to the *IRAS* fluxes suggests that the grain temperature, $T_{dust} = 110$ K (Jura et al. 1995).

Previous studies of circumstellar gas around HR 4796A have not been very successful. Searches for millimeter and submillimeter emission from CO (J=3→2, J=2→1,

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J=1→0), used as a tracer for H$_2$, have failed (Zuckerman et al. 1995, Liseau 1999, & Greaves et al. 2000), perhaps because the angular size of the source as measured in the infrared is significantly smaller than the beam of available telescopes. Another possibility is that circumstellar molecular gas is not present because it is rapidly photodissociated under the intense stellar ultraviolet field of the central A0V star. Holweger, Hempel, & Kamp (1999) have detected two narrow, circumstellar Ca II K absorption features, one component close to the stellar velocity and another weaker one blueshifted by ∼10 km/sec which they attribute to possible circumstellar gas.

2. OBSERVATIONS

HR 4796A was observed with the *Far Ultraviolet Spectroscopic Explorer* (*FUSE*) for 12.4 ksec on 2002 April 25 in histogram mode, using the low resolution 30″ × 30″ aperture which covers the wavelength range between 905 and 1187 Å. This wavelength coverage allows us to search for circumstellar absorption in the ground states of C II λ1036.3 and O I λ1039.2, and in Lyman series H$_2$. The *FUSE* satellite has four channels (LIF 1, SIC 1, LIF 2, SIC 2) which form two nearly identical "sides" (labeled 1 and 2) that each consist of a LIF grating, a SIC grating, and a detector. Each detector is divided into two independent segments (A and B), seperated by a small gap. The eight partially overlapping spectra that fall on different portions of the two detectors (LIF 1A, LIF 1B, etc.) cover the entire wavelength range. A description of the on orbit performance of *FUSE* is described in Sahnow et al. (2000) with a conservative estimate for the spectral resolution (R = $\lambda/\Delta\lambda$ = 15000) of the spectrograph. The data were calibrated at Johns Hopkins using the CALFUSE 1.8.7 pipeline.

HR 4796A was observed with Space Telescope Imaging Spectrograph (STIS) in echelle mode on the *Hubble Space Telescope* (*HST*) for 930 sec and 550 sec on 2002 August 22, with the E140H and E230H gratings respectively using the 0.2″×0.09″slit. The spectra covered the wavelength regions 1425 Å - 1620 Å and 1880 Å - 2155 Å with a spectral resolution (R = $\lambda/\Delta\lambda$ = 220,000). This wavelength coverage allows us to search for circumstellar absorption in the ground state of Zn II λ2026.1 and in CO (A-X). The data were calibrated at the Space Telescope Science Institute using the standard STIS software package *calstis*, executed under the OPUS pipeline.

We observe absorption in the ground states of Si II at 1526.14 Å, Fe II at 1608.45 Å, and Zn II at 2026.14 Å along the line of sight to HR 4796A (see Figure 1). The Si II and Fe II lines possess two absorption components, one at about -5 km/sec and another at about -15 km/sec, consistent with the Ca II results from Holweger et al. (1999). We believe that both gas components are interstellar. Circumstellar gas in Keplerian orbit at 70 AU from an A0V star would have a velocity of ∼5.5 km/sec. Therefore, any circumstellar gas features will be indistinguishable from interstellar lines on the basis of line width. However, circumstellar gas at 70 AU from an A0V should be radiatively pumped, populating the excited fine structure lines. We observe no absorption in the Si II* line at 1533.43 Å, suggesting that the Si II gas is interstellar. Since the Fe II line has the same velocity structure as the Si II line, this ma-

terial is probably also interstellar. Even though the Zn II line only possesses one velocity component, its velocity is similar to that of the Si II and Fe II components near the stellar velocity.

We observe no absorption in the H$_2$ Lyman (5,0) band or the CO A-X (1,0) band toward this star. The 3σ upper limits on the H$_2$ line-of-sight column densities in the J = 0 and J = 1 rotational levels are measured, from the P(1) and R(0) transitions at 1036.54 Å and 1038.16 Å, to be $N(J = 0) \leq 10^{15}$ cm^{-2} and $N(J = 1) \leq 3.7 \times 10^{15}$ cm^{-2} using wavelengths and oscillator strengths from Abgrall et al. (1993). The 3σ upper limits on the CO line-of-sight column densities in the J = 1 and J = 2 rotational levels are measured, from the R(0) and R(1) transitions at 1544.45 Å and 1544.39.73 Å, to be $N(J = 1) \leq 1.2 \times 10^{13}$ cm^{-2} and $N(J = 2) \leq 2.4 \times 10^{13}$ cm^{-2} using wavelengths and oscillator strengths from Morton & Noreau (1994). Similarly, we observe no absorption in C II λ1036.3 and O I λ1039.2, and no circumstellar absorption in Zn II λ2026.1 a tracer for atomic hydrogen in the interstellar medium (York & Jura 1982). The 3σ upper limits on these column densities are $N(C II) \leq 1.4 \times 10^{14}$ cm^{-2}, $N(O I) \leq 2.8 \times 10^{15}$ cm^{-2}, and $N(Zn II) \leq 2.6 \times 10^{12}$ cm^{-2} and are estimated using oscillator strengths from Morton (1991). We calculate equivalent width upper limits assuming circumstellar line widths of 5.5 km/sec for the STIS data. We calculate equivalent width upper limits assuming circumstellar line widths of 2 resolution elements, after binning the data to a resolution of 0.05 Å or ∼29 km/sec for the *FUSE* data.

3. DISK VERTICAL STRUCTURE

Circumstellar gas in the low density environments around Vega-type stars is primarily heated via photoelectrons ejected from dust grains by stellar ultraviolet photons and primarily cooled by radiation from the [C II] fine structure line at 157.5 μm (Kamp & van Zadelhoff 2001). HR 4796A possesses an M-type companion, located 7.7″ away from the star. The companion has a *ROSAT* 0.1 - 2.4 keV luminosity, L$_x$ = 1.5 ×10^{29} ergs/sec (Jura et al. 1998) which corresponds to an X-ray flux of $F_x \leq 2 \times 10^{-4}$ ergs s^{-1} cm^{-2} at the position of HR 4796A. We estimate the photoelectric and X-ray heating rates for the gas around HR 4796A to determine whether X-ray heating plays an important role in this circumstellar environment.

The photoelectric heating rate for micron-sized silicate grains, like the ones found around HR 4796A (Augereau et al. 1999; Li & Lunine 2003), is

$$\Gamma_{pe} = 2.5 \times 10^{-4} \sigma \epsilon \chi n_H \qquad (1)$$

(Kamp & van Zadelhoff 2001) where n_H is the number density of hydrogen, σ is the grain cross section per hydrogen nucleus, ϵ is the photoelectric efficiency, and χ is the 912 - 1110 Å photon flux measured in units of the Habing field ($F_H = 1.2 \times 10^7$ cm^{-2} s^{-1}). At a distance of 70 AU from HR 4796A, we estimate $\chi = 460$ from our *FUSE* spectra, roughly consistent with a Kurucz stellar atmosphere with T_{eff} = 10,000 K, log g = 4.0, and solar metallicity (Fajardo-Acosta, Telesco, & Knacke 1998). For large silicate grains, the dust UV cross section $\sigma = 2.34 \times 10^{-21}/\delta$ cm^2 H-atom^{-1} where δ is the gas:dust ratio and ϵ = 0.06 for low temperatures. If the gas:dust ratio is 4 (σ = 5.85 × 10^{-22} cm^2 H-atom^{-1}), ϵ = 0.06, and χ = 460,

then the photoelectric heating rate is $\Gamma_{pe} = 4.0 \times 10^{-24} n_H$ ergs cm^{-3} s^{-1}.

The X-ray heating rate for a cold neutral gas is

$$\Gamma_x = f_h \sigma_x F_x n_H \qquad (2)$$

where $f_h (\sim 0.3)$ is the fraction of the absorbed X-ray energy that heats the gas, σ_x is the X-ray cross section due to all atoms per hydrogen nucleus, and F_x is the X-ray flux. If the bulk of the X-ray energy is carried by 0.5 keV photons, then the cross section $\sigma_x = 1.65 \times 10^{-21}$ cm^2 (Maloney, Hollenbach, & Tielens 1996). If $F_x \leq 2 \times 10^{-4}$ ergs s^{-1} and $\sigma_x = 1.65 \times 10^{-21}$ cm^2, then $\Gamma_x \leq 9.9 \times 10^{-26} n_H$ ergs cm^{-3} s^{-1}, suggesting that X-ray heating is not significant in the optically thin regime. X-ray heating in more gaseous circumstellar disks is even less important because the disk becomes optically thick to the X-ray radiation.

Kamp & van Zadelhoff have derived an analytic approximation for the gas temperature assuming that the gas is heated by photoelectrons ejected by dust grains and is cooled via [C II] line emission at 157.7 μm. In this case, the gas temperature

$$T_{gas} = \frac{91.98 \text{ K}}{\log[2(\frac{\epsilon_C A_{10} h\nu_{10}}{2.5 \times 10^{-4} \epsilon \sigma \chi} - 1)]} \qquad (3)$$

where ϵ_C is the carbon abundance, A_{10} and $h\nu_{10}$ are the Einstein A coefficient and energy carried by the photon in the C II transition. For the 157.7 μm [C II] line, $A_{10} = 2.4 \times 10^{-6}$ s^{-1} and $h\nu_{10} = 1.27 \times 10^{-14}$ ergs. If the circumstellar environment around HR 4796A possesses a solar carbon abundance, then $\epsilon_C = 4.6 \times 10^{-4}$ and the gas temperature $T_{gas} = 65$ K. If the carbon abundance is interstellar $\epsilon_C = 1.4 \times 10^{-4}$, then the cooling via carbon emission will be less efficient and the circumstellar gas will be hotter. In Figure 2, we plot the gas temperature as a function of the circumstellar gas mass (or gas:dust ratio) as inferred from equation (3). For HR 4796A, this approximation only holds for the outer portions of the disk. For example, O I is an important coolant at the inner edge of the disk midplane. In addition, this approximation breaks down for HR 4796A models with gas:dust ratio larger than a few. In higher gas:dust ratio models, the implied gas densities are large enough to allow CO to become self shielding, unlike the circumstellar disk models around Vega, because the HR 4796A circumstellar disk is more compact. In these cases, the cooling also becomes more complicated.

We assume that the circumstellar gas is in hydrostatic equilibrium. In this model, the gas number density, n, can be written as a function of the height above the disk midplane, z,

$$n(z) = n_o e^{-\frac{1}{2}(\frac{z}{H})^2} \text{ where } \frac{H}{R} = (\frac{kT_{gas}R}{\mu G M_*})^{\frac{1}{2}} \qquad (4)$$

where H is the disk thickness parameter, R is the distance to the star, M_* is the stellar mass, and μ is the mean molecular weight of the gas. If the gas is primarily H$_2$ with [He]/[H$_2$] = 0.2 so that $\mu = 3.9 \times 10^{-24}$ g. If the gas is primarily H I with [He]/[H$_2$] = 0.1, then $\mu = 2.2 \times 10^{-24}$ g. Since HR 4796A is not viewed edge-on, successful detection of circumstellar gas (or the establishment of meaningful gas mass upper limits) via absorption line studies requires that the disk thickness parameter, $H \sim$

$R \sin i$. Smaller thickness parameters lead to less puffed-up disks which provide fewer gas atoms and molecules along the line of sight. The inclination and the radius of the HR 4796A disk has been measured to be $\sim 17°$ from edge-on and 70 AU (Schneider et al. 1999) suggesting that a disk thickness parameter of ~ 10 AU is necessary. If the gas is molecular, $M_* = 2.4 M_\odot$, and $T_{gas} = 65$ K, then the thickness parameter $H = 6.1$ AU at $R = 70$ AU and our line of sight intercepts the gas at 3.4 H above the disk. If the gas is atomic, then the thickness parameter $H = 8.1$ AU at $R = 70$ AU and our line of sight intercepts the gas at 2.5 H above the disk.

4. GAS MASS ESTIMATES

We estimate the gas mass upper limits from our line-of-sight column density upper limits for molecular and atomic gases assuming that the gas species are well-mixed and in hydrostatic equilibrium. (i.e. If the gas is molecular, we will assume a disk thickness parameter $H = 6.1$ AU for both CO and H$_2$ despite the fact that CO molecules are more massive than H_2 molecules. If the gas is atomic, we will assume a disk thickness parameter $H = 8.1$ AU for C II, O I, and Zn II.) To estimate the circumstellar gas mass from the column density upper limits, we must assume a particular gas mass surface density, Σ. For simplicity, we assume that the gas and dust have the same radial distribution. If the dust and gas are not cospatial then photoelectric heating will not effectively warm the gas and the gas temperature will be significantly colder than 65 K.

$$\Sigma(R) = \Sigma_0 \begin{pmatrix} d\left(\frac{R}{R_0}\right)^{-2.5} & \text{if} & R < R_1 \\ e^{-\frac{(R-R_0)^2}{\delta R_0^2}} & \text{if } R_1 \leq R \leq R_0 \\ \left(\frac{R}{R_0}\right)^{-2.5} & \text{if} & R > R_0 \end{pmatrix} \qquad (5)$$

(Klahr & Lin 2000) where $R_0 = 70$ AU is the peak of the dust distribution, $\delta R_0 = 10$ AU, and $d = 0.9$ (which corresponds to $R_1 = 68.1$ AU). We can write an expression for the gas density from equations (4) and (5)

$$n(r, z) = \frac{\Sigma(r)}{\sqrt{2\pi} H(r)} e^{-\frac{1}{2}(\frac{z}{H(r)})^2} \qquad (6)$$

We estimate the column density by integrating the mass density in equation (6) along the line-of-sight. If the line of sight is inclined $i°$ from the disk midplane, then the estimated column density, N, is

$$N = \frac{1}{m_s \cos i \sqrt{2\pi}} \int_{R_{in}}^{R_{out}} \frac{\Sigma(R)}{H(R)} e^{\frac{-\sin^2 iR^2}{2H(R)^2}} dR \qquad (7)$$

where m_s is the mass of the species of interest, $i = 17°$, $T_{gas} = 65$ K, $M_* = 2.4 M_\odot$, $R_{in} = 60$ AU and $R_{out} = 80$ AU.

If we set the estimated column density to be less than or equal to the observed column density upper limit, we can establish an upper limit for Σ_0. Once Σ_0 is known, estimating the circumstellar gas mass upper limit only requires integrating the mass surface density. For molecular gas around HR 4796A, the gas mass in species s can be written as the following expression:

$$M_{gas} \leq 2.9 \times 10^{-4} \left(\frac{N}{10^{15}\text{cm}^{-2}}\right) \left(\frac{m_s}{\mu}\right) M_\oplus \qquad (8)$$

where N is the measured column density. The J = 0 and J = 1 H$_2$ column density upper limits listed in Table 3 suggest H$_2$ gas masses of $\leq 2.5 \times 10^{-4}$ $M_\oplus$ and $\leq 9.1 \times 10^{-4}$ $M_\oplus$, respectively. This result suggests that the HR 4796A circumstellar disk possesses very little molecular gas.

The nondetection of H$_2$ around HR 4796A may not be surprising because HR 4796A, an A0V star, produces a high ultraviolet photon flux which is capable of rapidly photodissociating molecular gas. Therefore, we also searched for absorption due to circumstellar O I, C II, and Zn II, a tracer for atomic hydrogen in the interstellar medium (York & Jura 1983). We can estimate the gas mass assuming that the bulk of the gas is predominately atomic.

$$M_{gas} \leq 3.3 \times 10^{-5} \left(\frac{N}{10^{15} \text{cm}^{-2}} \right) \left(\frac{m_s}{\mu} \right) M_\oplus \qquad (9)$$

We list gas mass upper limits for each of the atomic species in Table 3 using equation (9). We also infer atomic hydrogen disk mass upper limits assuming that the composition of the circumstellar gas is approximately solar.

$$M_H \leq 1.4 \times 10^{-8} \frac{1}{\epsilon_s} \left(\frac{N}{10^{12} \text{cm}^{-2}} \right) M_\oplus \qquad (10)$$

where ϵ_s is the abundance of the species of interest. For $\epsilon_O = 8.1 \times 10^{-4}$, $\epsilon_C = 4.6 \times 10^{-4}$, and $\epsilon_{Zn} = 3.8 \times 10^{-8}$ (Gray 1992), we find $M_H \leq 1.0$ $M_\oplus$. Since submillimeter continuum measurements estimate ≥ 0.25 $M_\oplus$ dust around HR 4796A (Greaves et al. 2000), our hydrogen gas mass upper limit corresponds to a gas:dust mass ratio of ≤ 4.0.

If circumstellar gas is in hydrostatic equilibrium, then any gas mass estimates are dependent on the inferred gas temperature. The density depends on the exponential of $-(1/H)^2$; therefore, small changes in the disk thickness parameter can lead to dramatic changes in the inferred gas mass. We plot the inferred H I mass from our Zn II column density upper limit as a function of gas temperature in Figure 3. For example, changing the gas temperature from 65 K to 28 K corresponds to changing the disk thickness parameter from 8.1 AU to 5.3 AU and the inferred H I mass from ≤ 1.0 $M_\oplus$ to 40 $M_\oplus$. This corresponds to a gas:dust ratio ≤ 160, approximately the interstellar gas:dust ratio.

5. THE GAS TEMPERATURE AND DISK CHEMISTRY

Kamp & van Zadelhoff (2001) have produced detailed numerical models of circumstellar gas heating and cooling around main sequence A-type stars to calculate the gas temperature and chemistry. Given a prescribed gas and dust density distribution, these models solve the chemistry and energy balance of the gas self-consistently on a two dimensional grid. The computation proceeds along a number of rays originating at the star's position under various angles. Typically, 500 radial gridpoints and 30 angles covering about 3 scaleheights are considered. The heating in low density disks, like the one found around HR 4796A, is dominated by photoelectrons ejected from circumstellar dust grains by stellar ultraviolet photons. Kamp & van Zadelhoff (2001) use ATLAS9 models to estimate stellar photospheres and assume that circumstellar dust grains are large silicate grains with radius, $a = 3$ μm, and density, $\rho = 3.0$ g cm^{-3}. They assume a dust UV extinction cross section $\sigma_{UV} = 2.34 \times 10^{-21}/\delta$ cm^2 (H-atom)$^{-1}$ and a fixed fraction of vibrationally excited H$_2$, $f_{H_2^*} = 1.0 \times 10^{-5}$.

We have improved the Kamp & van Zadelhoff (2001) models by making the following changes: (1) including cosmic ray reactions, (2) lowering the temperature for CO freeze out to ~ 20 K, (3) including an escape probability formalism for line photons (Tielens & Hollenbach 1985; TH85), and (4) calculating the statistical equilibrium for C II following the approach used for O I and CO by Kamp & van Zadelhoff (2001). Cosmic ray reactions are added to make the code more general. This change does not affect the result described here because the chemistry around main sequence A-type stars is driven by stellar photons. The escape probability formalism is necessary because the main cooling lines, such as [O I] and CO, become optically thick for disks with gas:dust ratios of 10 and 100. The escape probability of a line photon, β, is conservatively estimated from the line optical depth towards the star at each gridpoint. Since the optical depth perpendicular to the disk is much lower than the optical depth in the disk midplane, our estimates yield reasonable lower limits for the line cooling and therefore reasonable upper limits for the gas temperature. We also include a model which does not contain the one dimensional escape probability approximation to estimate the possible error arising from this approach.

We have modeled the circumstellar gas around HR 4796A using the model described above with a gas density distribution,

$$n(r) = n_i \left(\frac{R}{R_i} \right)^{-2.5} e^{-\frac{1}{2}(\frac{z}{H})^2} \qquad (11)$$

where R_i is the inner disk radius and n_i is the gas density at R_i. We assume that the density distribution is fixed a priori with a disk thickness parameter $H \propto R$ and $H/R = 0.12$. For HR 4796A, we further assume $R_i = 60$ AU and an outer disk radius $R_o = 80$ AU. The disk thickness parameter $H = 8.4$ at 70 AU is approximately consistent with our estimate for an atomic gas scale height, $H = 8.1$ AU (see Section 4). We fix the dust mass $M_{dust} = 0.25$ $M_\oplus$ and calculate the gas chemistry and temperature distribution assuming gas:dust ratios of 2, 10, and 100. An additional gas:dust ratio = 100 model is calculated assuming a constant escape probability, $\beta = 1$. The model parameters are summarized in Table 4.

The calculated temperature structures for the HR 4796A circumstellar disk models are shown in Figure 3. Deep inside the disk, [O I] and [C II] cooling balance photoelectric heating and heating by H$_2$ formation. With increasing gas mass, fine-structure line cooling becomes more efficient while photoelectric heating remains constant. The photoelectric heating rate does not change because the dust mass is fixed in all of the models. Thus, more massive disk models possess significantly cooler top layers. Since the one dimensional escape probability is only a crude approximation to the actual escape probabilty, we also model the HR 4796A disk with $\beta = 1$ for a gas:dust ratio of 100 (in which the [O I] 63 μm line has an optical depth of ~ 10 at 80 AU). In addition to escape along the line of sight to the star, line radiation can also escape perpendicular to the disk and through the outer radius. Therefore, models which include the one dimensional escape probability approximation yield an upper limit to the disk midplane gas temperature while models with $\beta = 1$ yield a lower

limit. The gas temperatures estimated with and without the one dimensional escape probability approximation differ by less than a factor of 2 or by less than 30% in the disk thickness parameter.

In Table 5, we list the predicted gas temperatures averaged over one scaleheight at 70 AU and the predicted H I, H_2, Zn II, C II and CO gas column densities assuming a line-of-sight inclined $17°$ from the disk midplane. The column densities estimated from these detailed heating and cooling models suggest that the measured column densities are not constraining, that the gas:dust ratio = 100 model is allowed for all species, except for C II. The measured C II column density, N(C II) = 1.4×10^{14} cm^{-2}, is most consistent with the $M_{gas} = 0.5\ M_\oplus$ model calculated using the 1-D escape probability approximation which predicts N(C II) = 1.5×10^{14} cm^{-2}. This result is consistent with the simple analytical estimate for the gas mass, $M_{gas} \leq 1.0\ M_\oplus$

6. DISCUSSION

In general, the simple analytic model and the detailed chemical model estimate similar temperatures and gas masses for the circumstellar disk around HR 4796A. The discrepancy between the predicted Zn II column densities from the simple analytical model and the detailed chemical model may be due to (1) the lack of detailed structure in the simple model and (2) the different surface density distributions used. In the simple model, the entire disk is assumed to be either atomic or molecular even though the disk possesses a more complicated chemical structure. For the low gas:dust ratio case, the upper regions of the disk are predominantly atomic while the midplane consists of cooler molecular material. The line-of-sight intercepts the upper layer of atomic hydrogen but few molecules of cooler H_2. The surface density, Σ, in the simple model is a Gaussian superimposed on a $R^{-2.5}$ power law while the surface density in the chemical model is only described by a $R^{-2.5}$ power law. Despite the difference in assumed functions, the surface densities in the models agree to within a factor of two at all radii in the disk suggesting that this difference can not account for the discrepancy in the predicted Zn II column densities.

The circumstellar disk around HR 4796 probably possesses $\leq 1.0\ M_\oplus$ H I which corresponds to a gas:dust ratio ≤ 4.0 although a gas:dust ratio of 100 can not be definitively ruled out. The atmosphere of a giant planet contains approximately 275 $M_\oplus$ of H_2 (Tholen, Tejfel, & Cox 2000). This is substantially more than either $\leq 1.0\ M_\oplus$ circumstellar gas we infer to exist around HR 4796A or even the $\leq 5.0\ M_\oplus$ gas that would exist if the gas:dust ratio were interstellar. Therefore, there is currently not enough circumstellar gas around HR 4796A to form the atmosphere of a Jovian planet. If Jupiters exist around HR 4796A,

they must have formed within $\sim$8 Myr, significantly less time than is required by multi-stage accumulation (10 - 100 Myr).

7. CONCLUSIONS

We have obtained ultraviolet spectra (905 Å - 1187 Å, 1425 Å - 1620 Å, 1880 Å - 2155 Å) of the nearby, debris disk object HR 4796A using *FUSE* and STIS on *HST*. We argue the following:

1. The X-ray flux from the M-dwarf companion HR 4796B does not significantly heat circumstellar gas around HR 4796A. The estimated X-ray heating rate is at least $\sim$40 times smaller than the estimated photoelectric heating rate.

2. Circumstellar gas around HR 4796A may be warmed to a temperature $T_{gas} \sim 65$ K by photoelectric heating if the gas:dust ratio is 4, suggesting a molecular gas disk thickness parameter $H = 6.1$ AU and an atomic gas disk thickness parameter $H = 8.1$ AU at 70 AU from the star. This is approximately consistent with detailed heating and cooling models which suggest a maximum gas temperature, T_{gas} 61 K, for a gas:dust ratio of 2, assuming a 1-D approximation for the escape probability of line photons.

3. The circumstellar disk around HR 4796A possesses very little H_2. We estimate that $\leq 1.1 \times 10^{-3}\ M_\oplus$ H_2 exists around HR 4796A assuming that gas is in hydrostatic equilibrium, is well-mixed, and has a temperature $T_{gas} = 65$ K.

4. We estimate that $\leq 1.0\ M_\oplus$ atomic hydrogen exists around HR 4796A. This corresponds to a gas:dust mass ratio ≤ 4.0 assuming that gas is in hydrostatic equilibrium, is well-mixed, and has a temperature $T_{gas} = 65$ K.

5. Measurements of C II column density may provide the strongest constraint on the gas mass in the HR 4796A circumstellar disk. While the measured H_2, CO, and Zn II column densities are consistent with the column densities predicted for the gas:dust ratio = 100 model, the measured C II column denisty N(C II) = 1.4×10^{14} cm^{-2} is most consistent with the gas:dust ratio = 2 model.

6. The circumstellar disk around HR 4796A is too gas depleted to support the formation of giant planets. Any Jovian planets in this system must have formed on a timescale ≤ 8 Myr.

REFERENCES

Abgrall, H., Roueff, E., Launay, F., Roncin, J.-Y., & Subtil, J.-L. 1993, A&AS, 101, 273
Augereau, J. C., Lagrange, A. M., Mouillet, D., Papaloizou, J. C. B., & Grorod, P. A., A&A, 348, 557
Boss, A. 2000, ApJ, 536, L101
Fajardo-Acosta, S., Telesco, C. M., & Knacke, R. F. 1998, AJ, 115, 2101

Gray, D. F. 1992, The Observation and Analysis of Stellar Photospheres (Bristol: Cambridge University Press)
Greaves, J. S., Mannings, V., & Holland, W. S. 2000, Icarus, 143, 155
Herczeg, G. J., Linsky, J. L., Valenti, J. A., Johns-Krull, C. M., & Wood, B. E. 2002, ApJ, 572, 310
Hoffleit, D., & Warren, W. H. 1991, The Bright Star Catalogue (5th ed.; New Haven: Yale Univ. Obs.)

Holweger, H., Hempel, M., & Kamp, I. 1999, A&A, 350, 603

Jayawardhana, R., Fisher, S., Hartmann, L., Telesco, C., Pina, R., & Fazio, G. 1998, ApJ, 503, L79

Jura, M. 1991, ApJ, 383, L79

Jura, M., Ghez, A. M., White, R. J., McCarthy, D. W., Smith, R. C., & Martin, P. G. 1995, ApJ, 445, 451

Jura, M., Malkan, M., White, R., Telesco, C., Pina, R., & Fisher, R. S. 1998, ApJ, 505, 897

Jura, M. 2003, to appear in in ASP Conf. Ser., Debris Disks and the Formation of Planets, eds. D. Backman, M. Meyer, & L. Caroff (San Francisco: ASP)

Kamp, I. & van Zadelhoff, G.-J. 2001, A&A, 373, 641

Klahr, H., & Lin, D. 2000, ApJ, 554, 1095

Koerner, D. W., Ressler, M. E., Werner, M. W., & Backman, D. E. 1998, ApJ, 503, L83

Lecavelier des Etangs, A., Vidal-Madjar, A., Roberge, A., Feldman, P. D., Deleuil, M., André, M., Blair, W. P., Bouret, J.-C., et al. 2001, Nature, 412, 706

Li, Aigen, & Lunine, J. I. 2003, ApJ, 590, 368

Liseau, R., & Artymowicz, P. 1998, A&A, 334, 935

Maloney, P. R., Hollenbach, D. J., & Tielens, A. G. G. M. 1996, ApJ, 466, 561

Morton, D. C. 1991, ApJS, 77, 119

Morton, D. C., & Noreau, L. 1994, ApJS, 95, 301

Richter, M. J., Jaffe, D. T., Blake, G. A., & Lacy, J. H. 2002, ApJ, 572, L161

Royer, F., Grenier, S., Baylac, M.-O., Gomez A. E., Zorec, J. 2002, A&A, 393, 897

Ruden, S. 1999, in The Origins of Stars and Plantary Systems, eds. C. J. Lada and N. D. Kylafis (Dordrecht: Kluwer Academic Publishers)

Sahnow, D. J., Moos, H. W., Friedman, S. D., Blair, W. P., Conard, S. J., Kruk, J. W., Murphy, E. M., Oegerle, W. R. et al. 2000, SPIE, 4139, 131

Schneider, G., Smith, B. A., Becklin, E. E., Koerner, D. W., Meier, R., Hines, D. C., Lowrance, P. J., Terrile, R. J., Thompson, R. I., & Rieke, M. 1999, ApJ, 513, L127

Stauffer, J. R., Hartmann, L. W., & Barrado y Navascués, D. 1995, ApJ, 454, 910

Telesco, C. M., Fisher, R. S., Pina, R. K., Knacke, R. F., Dermott, S. F., Wyatt, M. C., Grogan, K., Holmes, E. K. et al. 2000, ApJ, 530, 329

Thi, W. F., Blake, G. A., van Dishoeck, E. F., van Zadelhoff, G. J., Horn, J. M. M., Becklin, E. E., Mannings, V., Sargent, A. I., et al. 2001, Nature, 409, 60

Tholen, D. J., Tejfel, V. G., & Cox, A. N. 2000, in Allen's Astrophysical Quantities, ed. A. N. Cox (New York: Springer-Verlag), 293

Tielens, A.G.G.M., Hollenbach, D. 1985, ApJ, 291, 722

Weinberger, A., Becklin, E., & Schneider, G. 2000, in ASP Conf. Ser. 219, Disks, Planetesimals, and Planets, ed. F. Garzon, C. Eiroa, D. de Winter, & T. J. Mahoney (San Francisco: ASP), 329

Wyatt, M. C., Dermott, S. F., Telesco, C. M., Fisher, R. S., Grogan, K., Holmes, E. K., & Pina, R. K. 1999, ApJ527, 918

York, D. F., & Jura, M. 1982, ApJ, 254, 88

Zuckerman, B., Forveille, T. & Kastner, J. 1995, Nature, 373, 494

TABLE 1

HR 4796A PROPERTIES

Quantity	Adopted Value	Reference
Primary Spectral Type	A0V	1
Distance	67.1±3.4 pc	2
Effective Temperature (T_{eff})	10,000±500 K	
Stellar Radius (R_*)	1.7 $R_\odot$	2
Stellar Luminosity (L_*)	21 $L_\odot$	2
Stellar Mass (M_*)	2.4 $M_\odot$	
Rotational Velocity ($v \sin i$)	152±8 km/sec	3
Fractional Dust Luminosity (L_{IR}/L_*)	5×10^{-3}	2
Estimated Age	8±2 Myr	4
Grain Temperature	110 K	2
Dust Distance (R_0)	70±1 AU	5
Dust Mass (M_{dust})	≥0.25 $M_\oplus$	6

References. — (1) Hoffleit & Warren (1991); (2) Jura et al. (1998); (3) Royer et al. (2002); (4) Stauffer et al. (1995); (5) Schneider et al. (1999); (6) Greaves et al. (2000)

TABLE 2
INTERSTELLAR GAS PROPERTIES

Species	Wavelength (Å)	Ground State Energy (cm^{-1})	W_λ (mÅ)	N (cm^{-2})	v (km/sec)
Si II	1526.14	0.00	65	$\geq 2.4 \times 10^{13}$	-5.0
Si II	1526.14	0.00	20	$\geq 7.4 \times 10^{12}$	-14.4
Fe II	1608.45	0.00	14	$\geq 9.9 \times 10^{12}$	-5.5
Fe II	1608.45	0.00	15	$\geq 1.1 \times 10^{13}$	-14.6
Zn II	2026.14	0.00	7	$\geq 3.8 \times 10^{11}$	-6.0

TABLE 3
CIRCUMSTELLAR GAS UPPER LIMITS

Species	Wavelength (Å)	Ground State Energy (cm^{-1})	W_λ (mÅ)	N (cm^{-2})	M_{gas} ($M_\oplus$)	M_H ($M_\oplus$)	Gas:Dust Ratio
C II	1036.33	0.00	≤ 160	$\leq 1.4 \times 10^{14}$	$\leq 2.4 \times 10^{-5}$	$\leq 4.5 \times 10^{-3}$	≤ 0.018
O I	1039.23	0.00	≤ 250	$\leq 2.8 \times 10^{15}$	$\leq 6.4 \times 10^{-4}$	≤ 0.051	≤ 0.20
Zn II	2026.14	0.00	≤ 5	$\leq 2.6 \times 10^{12}$	$\leq 2.4 \times 10^{-6}$	≤ 1.0	≤ 4.0
H$_2$ (J=0)	1036.54	0.00	≤ 260	$\leq 1.0 \times 10^{15}$	$\leq 2.5 \times 10^{-4}$	$\leq 2.5 \times 10^{-4}$	$\leq 1.0 \times 10^{-3}$
H$_2$ (J=1)	1038.16	118.16	≤ 300	$\leq 3.7 \times 10^{15}$	$\leq 9.1 \times 10^{-4}$	$\leq 9.1 \times 10^{-4}$	$\leq 3.6 \times 10^{-3}$
CO (J=1)	1544.45	3.85	≤ 4	$\leq 1.2 \times 10^{13}$	$\leq 4.1 \times 10^{-5}$	N/A	N/A
CO (J=2)	1544.39	11.58	≤ 4	$\leq 2.4 \times 10^{13}$	$\leq 8.3 \times 10^{-8}$	N/A	N/A

TABLE 4
HR 4796A MODEL PARAMETERS

Model	M_{gas} ($M_\oplus$)	Gas:Dust Ratio	σ (cm^2/H-atom)	escape approach
Model 1	0.5	2	$1.17\,10^{-21}$	TH85
Model 2	2.5	10	$2.34\,10^{-22}$	TH85
Model 3	25.0	100	$2.34\,10^{-23}$	TH85
Model 4	25.0	100	$2.34\,10^{-23}$	$\beta = 1$

TABLE 5
MODEL PREDICTED GAS TEMPERATURES AND COLUMN DENSITIES

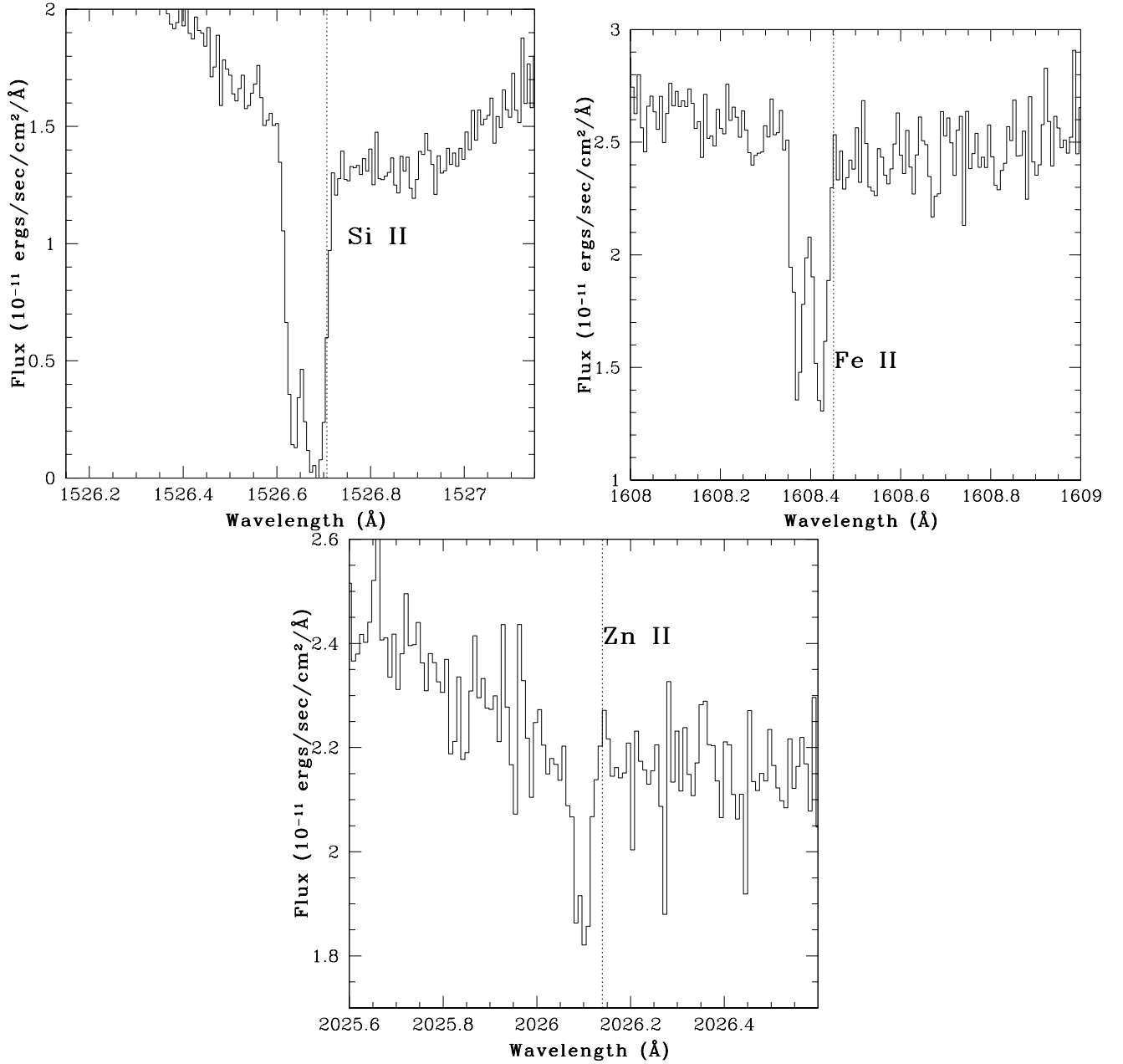| Model	Averaged T_{gas}(70 AU) (K)	Predicted N_H (cm^{-2})	Predicted N_{H2} (cm^{-2})	Predicted N_{Zn+} (cm^{-2})	Predicted N_{C+} (cm^{-2})	Predicted N_{CO} (cm^{-2})
Model 1	61	1.1×10^{18}	2.3×10^{13}	4.2×10^{10}	1.5×10^{14}	4.2×10^6
Model 2	45	5.3×10^{18}	8.4×10^{13}	2.0×10^{11}	7.5×10^{14}	1.1×10^8
Model 3	52	5.3×10^{19}	1.0×10^{15}	2.0×10^{12}	7.3×10^{15}	9.9×10^9
Model 4	22					

FIG. 1.— The interstellar (a) Si II λ 1526.71 and (b) Fe II λ 1608.45, and (c) Zn II λ 2026.14 lines obtained with STIS. The vertical lines indicate the wavelengths of the Si II, Fe II, and Zn II lines at the star's velocity..
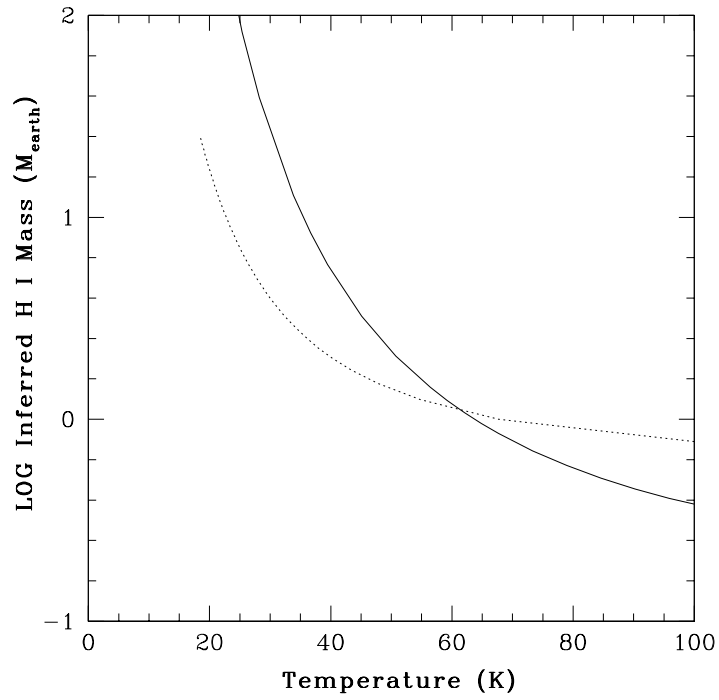
FIG. 2.— The gas temperature, estimated from equation (3) plotted as a function of the gas:dust ratio or gas mass (dotted line). The circumstellar gas mass upper limit inferred from the Zn II line at 2026.14 Å plotted as a function of gas temperature (solid line). In these simple models, the gas has a constant temperature throughout the disk. Both relationships constrain the circumstellar gas mass as a function of temperature.
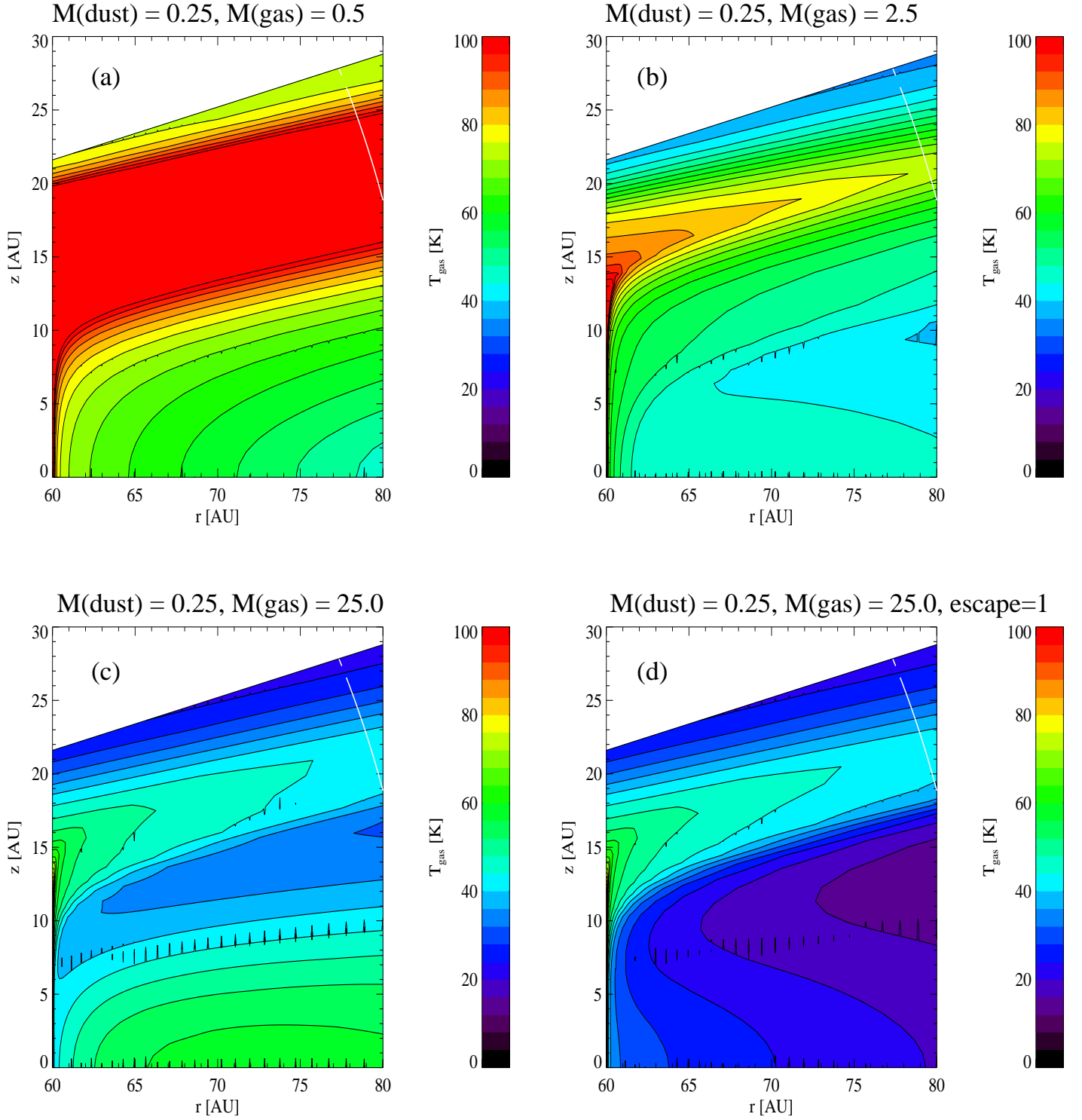
FIG. 3.— (a)-(c) The gas temperature structure in a slice perpendicular to the disk for models with gas:dust ratios of 2, 10, and 100, calculated using the one dimensional escape probability formalism discussed in the text, and (d) the temperature structure for a model with a gas:dust ratio of 100 calculated using $\beta = 1.0$